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To: Dr. Ray Orbach
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From: Gerald Blazey, Alfred Goshaw, Nigel Lockyer, and John Womersley
(Spokespersons of the CDF and DZero Experiments)

Please find attached a document prepared by the CDF and DZero collaborations that describes the physics program of Run II at the Fermilab Tevatron Collider. We have also included a one-page, non-technical summary.

Please refer to this memo in preference to that of December 10, 2002. The content is identical except that we have corrected an error in Figure 2.

Cc: James Decker
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Exploring the Universe with the Fermilab Proton-Antiproton Collider

The CDF and DZero collaborations
December 10, 2002

Physicists working at Fermilab's proton-antiproton collider have embarked on a quest to answer some of the **deepest questions about the basic fabric of the universe.** What is the **structure of space-time** and are there more than three dimensions of space? Are the forces we observe in nature merely different manifestations of **a single unified force** responsible for all motion in the universe, as Einstein long believed? Is there an **energy field** that fills the cosmos, and is it responsible for **mass**? Can the laws of the sub-atomic world explain the **development of the universe** and the stars and galaxies we now see in the sky?

The four-mile Fermilab Tevatron accelerator collides the world's most energetic beams of protons and antiprotons. The beams are so energetic that when individual protons and antiprotons collide, a great number and variety of sub-atomic particles are created, many of which have not been naturally produced since the early seconds of the universe. Operating in the mid-1990's, the CDF and DZero experiments discovered the top quark, by far the heaviest building block of matter. This is an essential component of the Standard Model, which successfully describes most of the sub-atomic world. This success makes it possible to further contemplate questions about the structure and development of the universe. With the completion of a five-year upgrade of the Fermilab accelerator complex and its two large detectors, more than a thousand experimenters are exploring these questions with vastly improved capability.

The data collected over the next few years will include thousands of top quarks. Their properties may reveal small inconsistencies in the Standard Model that would point us toward a more complete understanding of the laws of nature. Top quark characteristics will permit us to infer properties of the long sought Higgs boson, the object that would explain why elementary particles have mass and thus why the stable universe about us can exist.

Data taken through this decade may reveal even more about the big questions. We may go beyond inferring properties of the Higgs boson to directly observing it and measuring its properties. We might even discover an entirely new class of elementary particles, supersymmetric particles, which would be an enormous step toward finding a unified theory and, at the same time, the dark matter responsible for motions of the galaxies.

The Fermilab physics program could even lead to the discovery and exploration of additional dimensions of space, which may be "invisible" to us because they are too tiny for us to see. We could detect these new dimensions by creating gravitons, the quanta of gravity, in our collisions. Gravitons may be able to enter the extra dimensions, taking energy and momentum with them. The observation that we live in a world of more than three space dimensions would be a truly revolutionary scientific discovery.

Operating at the high energy frontier, with a sensitivity hundreds of times that achieved in previous data runs, the Fermilab collider program has the potential for revolutionizing our understanding of elementary particle physics and the microscopic structure of the universe. The combination of the upgraded Tevatron complex and the greatly improved detectors provides extraordinary opportunities for discovery. The research effort has now begun and will continue through this decade resulting in a new understanding of nature at its most fundamental level.

The Physics of Run II at the Tevatron

The CDF and DZero collaborations
December 10, 2002

Introduction

The physics goals of Run II are broad and fundamental. Run II is the only facility in operation that can help to answer all of these really big questions:

- What is the structure and what are the symmetries of space-time?
- Why is the weak force weak?
- What is the composition of cosmic dark matter?
- Why is matter-antimatter symmetry not exact?

We do this first by directly searching for particles and forces not yet known, including both those that are predicted or expected (like the Higgs boson and supersymmetry) and those that would come as a complete surprise. Second, we confront the Standard Model of particles and forces through precise measurements of the properties of the W, the Z and the top quark, through measurements of the quark mixing matrix, and through measurements of the electroweak force and the strong interaction.

The experiments already have first results in all of these areas, which have been presented at the International Conference on High Energy Physics in Amsterdam in summer 2002 and at the Hadron Collider workshop in September. They show that all the analysis tools are in place and ready at both CDF and DZero. In the rest of this document we will outline the present status and future prospects of the Run II physics program.

Operations

The Run II physics program is now underway. The CDF and DZero detectors are both working well and are recording physics quality data with emphasis on maximizing the data taking efficiency. CDF is running a trigger for B-mesons using displaced tracks from the silicon detector, which is a first at a hadron collider.

Computing for data processing and analysis is a challenge for modern experiments both because of the quantity of data and because of the size and distributed geography of the collaborations. In the past, this led to the invention of the world-wide web as a way to share information. Now the challenge is to share data and computing power. There is a natural synergy between the needs of our experiments and current ideas about “Grid” computing. The Tevatron experiments are already making something like a Grid a reality and are distributing their data for analysis using a Fermilab-developed system called

SAM. They are also exploring ways for remote collaborators to assist in monitoring detector operations using web tools over the internet.

Searching for New Physics

As the world's highest energy collider, the Tevatron is the most likely place to directly discover a new particle or force. Despite the enormous success of the standard model, we know that it is incomplete. For one thing, it does not include gravity, and for another it has a large number of unexplained parameters, such as the masses of the fundamental particles, that are not predicted by the theory. To explain why the masses of the fundamental particles are not all zero, the standard model requires a Higgs boson, but the mass of the Higgs itself is unpredicted, and moreover diverges to infinity due to higher-order corrections. A more complete theory is required to fix these unphysical effects. Theoretically the most popular extension is to make the standard model a part of a larger picture called supersymmetry (SUSY). Supersymmetry is a basic prediction of string theories. If supersymmetry applies at the electroweak scale, then each known particle has a so-far unobserved and more-massive partner, to which it is related through a change of spin. The universe could well contain vast numbers of the stable, lightest "super-particle," which would explain the astronomers' observations of dark matter in the universe. Because the Tevatron is the world's highest energy accelerator, it presents a unique opportunity for the discovery of supersymmetric particles, including the supersymmetric partners of quarks, gluons, leptons and W and Z bosons. Theories of supersymmetry make firm predictions for the production rates and decay channels of these particles, so our searches rely on well defined signatures. These searches were all performed in Run I, but the increased energy of the Tevatron in Run II, coupled with a much larger dataset and more sensitive detectors have greatly increased the discovery reach.

In Run II, the Tevatron will also experimentally test the new and exciting idea that gravity may propagate in more than four dimensions of space-time. If there are extra dimensions that are open to gravity, but not to the other particles and forces of the standard model, then we could not perceive them in our everyday lives. But particle physics experiments at the TeV scale could see signatures in which a graviton, produced along with other particles, escapes undetected into the extra dimensions carrying away momentum and energy and leaving behind an event with a significant energy-momentum imbalance. In addition to such direct evidence of gravitons, their existence could also be inferred from indirect indications like an increase in high energy electron-pair production. These studies will use the Tevatron to literally measure the shape and structure of space-time.

While it is good to be guided by theory, we should simultaneously remain open to discovering the unpredicted. Therefore both experiments intend to carry out quasi-model-independent (signature-based) searches, which just look for deviations from the Standard Model. Searches of this type were performed in Run I, and while no significant deviations from the standard model were found, there were a small handful of events of unexplained origin. With such a limited sample, no one can know if these events are the first hint of new physics or just a statistical fluctuation, but they are enough to excite us about the prospects for further explorations in Run II.

Both CDF and DZero are actively engaged in searches for new physics of all kinds, the predicted and the unpredicted. In some of these searches the signatures are in well understood channels, such as multi-electron or multi-muon final states, and preliminary results in these channels have already been produced. For example, DZero has already presented limits on the scale of extra dimensions, supersymmetry with photon signatures, and particles decaying to electrons plus jets. In other searches, a prerequisite to the identification of rare, abnormal events is a very detailed study of the characteristics of *normal* events in the largely new detectors in order to understand the backgrounds to new phenomena. These studies are underway now. By late winter 2003, many of these searches by CDF and DZero will exceed the sensitivity to new physics of currently existing searches. By the end of 2003, all of them will.

The Higgs Boson

In the standard model, the weak force is weak because the W and Z bosons interact with a field (called the Higgs field) that permeates the universe. This same field is what gives masses to all the fundamental fermions. It should be possible to excite this field and observe its quanta — the long sought Higgs boson. It is the last piece of the standard model, and also a key to understanding any beyond-the-standard-model physics like supersymmetry. Finding it is a very high priority, but will require large datasets because the production cross section is low and the irreducible backgrounds are large.

All of the properties of the Higgs are fixed in the standard model with the exception of its own mass. Its couplings and decays are all determined. A relatively light Higgs, with a mass in the range between the current lower bound (from LEP) of 114 GeV/c^2 and about 145 GeV/c^2, will decay mainly to a bottom-antibottom ($b\bar{b}$) quark pair. This gives a signature of two jets, which is almost impossible to extract from the huge background of two jets from unrelated ("background") processes. Instead, we will search for the production of a Higgs together with a W or Z boson. The W or Z decays a significant fraction of the time into an electron or a muon, and a high energy electron or muon is relatively easy to trigger on and isolate. We then have the simpler, but still very challenging, task of separating the signal of a W/Z plus a Higgs, from the background of a W/Z plus two jets. Right now, we are developing the foundations needed to do this in Run II: good jet resolution, high b-identification and trigger efficiencies, and a good understanding of all the backgrounds. These will also enable us to firm up our earlier estimates of Higgs sensitivity as a function of luminosity.

In supersymmetry, there is still a Higgs boson: in fact the existence of a light Higgs is a very basic prediction of SUSY. These models contain an extended suite of Higgs particles, one of which looks very much like the standard model Higgs. Searches for the standard Higgs therefore apply to its supersymmetric cousin as well; if we exclude the existence of such a Higgs, we have gone a long way to ruling out supersymmetry at the TeV scale. One area of Higgs physics that can be attacked with relatively modest luminosities already in 2003 is to search for one or more of these supersymmetric Higgs bosons. Associated production of a SUSY Higgs together with a $b\,\bar{b}$ quark pair is enhanced for some plausible values of certain SUSY parameters (high $\tan\beta$), and tighter limits than those from LEP can already be set with a few hundred inverse picobarns.

The Top Quark

If new types of particles are not directly observed in Run II, we have an excellent window for obtaining indirect evidence of new physics by studying the properties of the top quark. The top quark is unique among the elementary constituents of matter because of its high mass (175 times the proton mass, compared to 5 times the proton mass for the next heaviest quark). In the standard model this means that it alone has a strong (non-perturbative) coupling to the Higgs boson. Is nature giving us a hint here? Whether the Higgs or something else turns out to be the origin of the electroweak symmetry breaking, the top quark seems to be uniquely connected to the mechanism of mass generation, and the Tevatron collider is the world's only source of top quarks. We plan to use it to measure the top quark's properties with greatly increased statistics. Both DZero and CDF are on the road to "rediscovering" top for the spring 2003 conferences, and both experiments have candidate events. We can look forward to significant improvements in the short to medium term because the Run I dataset was so statistically limited — of order 20 clean events per detector. In Run II, we expect roughly 500 such clean events for every inverse femtobarn recorded. We plan to improve the cross section and mass measurements, look for top-antitop spin correlations which can tell us if the top is really the spin-½ object it should be, and observe single top production which allows a model-independent measurement of the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix element $|V_{tb}|$. New techniques are also being developed: DZero has reported a new, preliminary determination of the top mass using existing Run I data. The new technique makes use of more information per event, giving better discrimination between signal and background than the published 1998 analysis, and improves the statistical error equivalently to a factor 2.4 increase in the number of events. Run II will also test beyond-the-standard-model theories that predict unusual top properties, states decaying into top, and anomalously enhanced single top production.

We can also see new particles and forces indirectly through their effects on electroweak observables. One of the tightest constraints will come from combining improved determination of the masses of the top quark with that of the W boson. In the standard model, the masses of these two particles are related to the mass of the Higgs boson. The current state of affairs is shown in the figure below. The yellow band represents W and top mass sensitivities to standard model Higgs masses between 114 GeV/c^2 and 1000 GeV/c^2. Currently, the W mass is known to be M_W = 80,451 ± 33 MeV/c^2, the precision being dominated by LEP data, and the combined CDF+DZero top mass is M_{top} = 173.8 ± 5.2 GeV/c^2 These values are represented on the figure below by the green dashed circle. It is marginally inconsistent with the 114 GeV/c^2 lower limit on the standard model Higgs mass from LEP. With 2 fb^{-1} of Run II data we will be able to drive the uncertainty on M_W down to about 25 MeV/c^2 per experiment and on M_{top} down to about 3 GeV/c^2 per experiment. Measurements at these sensitivities will present a powerful test of the consistency of the standard model. With an ultimate capability of 15 MeV/c^2 for M_W and 1-2 GeV/c^2 for M_{top} per experiment, the indirect evidence for physics beyond the standard model would be compelling.

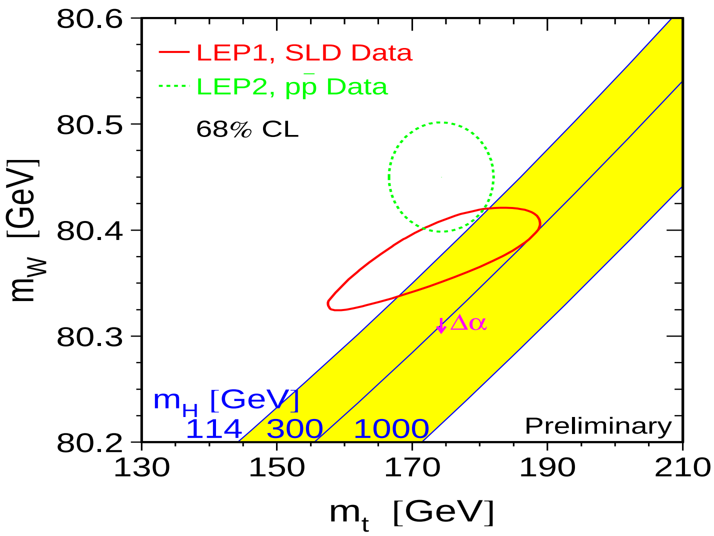

Figure 1. Top mass vs. W boson mass plane. The yellow band shows how the standard model Higgs boson mass is related to the measured value of the top and W masses (through electroweak radiative corrections). The latest data from LEP, combined with the Tevatron measurements is represented by the dashed elipse.

B-Physics and the Quark Mixing Matrix

The existence of three generations of quarks, and the mixing between them, results in subtle violations of the so-called CP symmetry relating particles and antiparticles. Understanding this symmetry will help explain why the universe is filled with matter, not antimatter. In the decays of B-mesons, these symmetry violations can be large, and so B-hadrons have become an important laboratory to explore the “unitarity triangle,” which relates the elements of the CKM matrix. If, as the standard model predicts, CP violation in the quark sector is governed by a single parameter in the CKM matrix, then the reason for our matter-dominated universe must lie elsewhere because standard model CP violation is far to small in magnitude to provide the answer. However, the quark-sector is the *only* place CP violation has been observed at all, so the possibility that its origins may go beyond the standard model is tantalizing, to say the least. In Run II we will confront the CKM matrix in ways that are complementary to the electron-positron B-factories.

CP violation in the B system is now firmly established at the B-factories in the decay of the B_d meson (a bound state of a bottom and an anti-down quark) . The measured mixing angle is consistent with the standard model, but also with new physics. To resolve this question, the BaBar and BELLE experiments can and will do much more with their data, but the Tevatron can uniquely access the B_s meson (in which the bottom quark is bound to an anti-strange quark, and which is not produced at the B-factories). The B_s system has been called the "el Dorado" for hadron collider B-physics and the world is waiting for our results. By measuring the mixing rate between B_s and $\overline{B}_s$, we can determine the length of one of the sides of the unitarity-triangle and complement the B-factories' measurements of its angles. CDF expects to be sensitive to standard model mixing with a few hundred inverse picobarns. There are many other opportunities to be pursued: we will look for CP violation both in decays where it is expected to be the same as in the B-factories and also where it is expected to be much smaller; we will measure certain B-meson decays that can be related to other decays measured at the B-factories, which together can pin down the unitarity triangle angles. We will also search for rare decays of B-mesons—a higher than expected rate would be an indirect signal of new physics. CDF already has most impressive B-physics results from Run II, building on their Run I experience together with new detector capabilities (silicon vertex trigger and time of flight detector). Data samples are being collected using both lepton-based triggers and the new Silicon Vertex Trigger. In DZero the tools are being put in place for a B-physics program: the inclusive B lifetime has been measured and DZero's first B mesons are being reconstructed.

The Strong Interaction

No one doubts that Quantum Chromodynamics (QCD) describes the strong interaction between quarks and gluons. Its effects are all around us: it is the origin of the masses of hadrons, and thus of the mass of stars and planets. This doesn't mean it is an easy theory to work with. As well as using hadron colliders to test QCD itself, we find that it is so central to the calculation of new physics processes, and their backgrounds, that we need to make sure we can have confidence in our ability to make predictions in this framework. We need to resolve some outstanding puzzles and ensure we understand how to calculate the backgrounds to new physics. These puzzles include measuring high-energy jets, which will constrain the gluon content of the proton at high momentum (currently poorly determined and a source of uncertainty) and understanding the higher-than-expected rates for heavy flavor (charm and bottom) production. Resolving this is important because many new particles result in heavy flavor signatures.

Near term and longer term future

By the summer of 2003, each experiment should have recorded around 200 pb^{-1} of Run II data (almost twice the Run I dataset). The centerpiece will be a greatly increased top quark sample, thanks to the slightly higher beam energy and the much improved b-tagging capabilities of the detectors. A first look at B_s mixing will be possible, together with lifetimes and measurements from the B, B_s and charm samples. Jet distributions at the highest energies will constrain proton structure, and searches will follow up on Run I anomalies and extend the Run I reach for many extensions to the standard model. With a factor of two increase in data sample and improved detectors, who knows what we will find?

For 2004 and beyond, it is clear that it will take somewhat longer than had been anticipated to accumulate the large datasets ultimately foreseen for Run II: such is the price of realism. It is just as clear that the ultimate datasets *will* be large enough to have an enormous impact on our knowledge and understanding of nature. As long as the Tevatron remains the world's highest energy collider, it is a unique facility that must be exploited to the full. We will run the Tevatron until the LHC experiments start producing competitive physics results. In light of our own experiences, we are under no illusions about how long it may take to bring the LHC online, and we are prepared to keep running the Tevatron until 2010. The Run II physics program is a broad and deep one and will answer crucial questions about the universe. As Figure 2 shows, there is no threshold at which this starts. There is compelling physics to be done each year, starting now with a few hundred inverse picobarns and gaining from each factor of two in luminosity. To explore the 5 fb^{-1} to 15 fb^{-1} domain calls for upgrades to the CDF and DZero detectors. Primarily, these involve new silicon detectors to handle higher radiation doses and trigger systems to deal with increased instantaneous luminosities. Without these upgrades, and without the needed investments in the accelerator complex, the full potential of Run II cannot be realized.

Run II is a marathon and not a sprint. The combination of high accelerator energy, excellent detectors and data samples that are doubling every year guarantees interesting new physics results at each step. Each step answers important questions. Each leads on to the next. This is how we will lay the foundations for a successful LHC physics program — and hopefully a linear collider to follow.

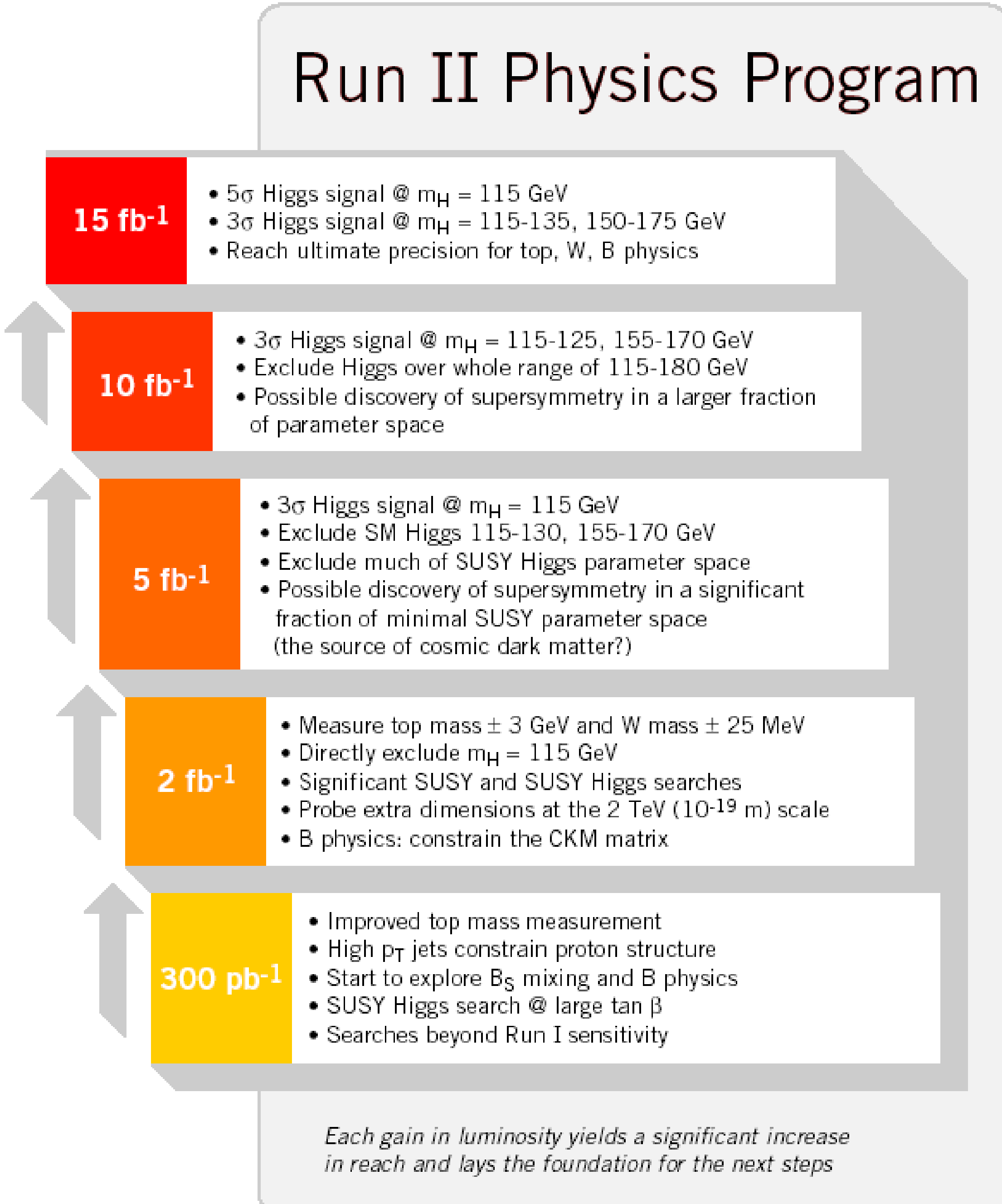

Figure 2: Summary of physics reach at various integrated luminosities.